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HIGH EXPLOSIVE DETONATION THRESHOLD SENSITIVITY DUE TO MULTIPLE FRAGMENT IMPACTS

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Fragments, bullets or projectiles can initiate a detonation in a high explosive (HE). For this to happen certain critical conditions need to be exceeded. For a given explosive, these critical conditions are the projectile velocity, the projectile size and shape, and the projectile material properties. A lot of work has been done in the area of metal shaped charge jets and individual fragments impacting the HE. One major gap in understanding initiation phenomena is the effect of multiple fragment impact. This study shows that multiple fragments can lower the fragment size and the kinetic energy thresholds.

INTRODUCTION

Traditionally, the proposed mechanism for initiating detonations in HE's has been centered on the notion that when micro voids/pores are rapidly compressed, they become hot spots. Since chemical reaction rates in HE's are typically a function of temperature and follow the Arrhenius behavior, increasing the temperatures beyond a threshold value could lead to a runaway reaction. If these hot spots are in sufficiently close proximity to each other, and there is a sufficient number of them, this reaction can lead to a detonation [1]. The conditions that determine whether the HE will detonate are governed by the competition between the birth rate, the growth rate, the death rate, and the coalescence rate of hot spots. This model of detonation is described by Nickols [2] This type of ignition and growth model predicts the sensitivity of HE ignition to three separate quantities. These three quantities are the magnitude of the pressure, the duration of the pressure, and the rate of pressure increase. All these quantities affect the collapse rate of voids/ formation of hot spots. If the voids are compressed slowly, the compression work raises the void temperature "slowly". If this rate is slower than the rate at which the energy is conducted away by thermal energy transport, then the temperature of the hot spots may not grow beyond threshold temperatures. This phenomena is illustrated by Fig 1 showing a range of possible responses of HE impacted by projectiles.

A fragment impacting the HE can produce a range of effects depending on its speed and size. A fast fragment will produce a higher pressure than a slow fragment. A large fragment will produce a pressure whose pulse width is longer than a small fragment. A large fragment will also spawn a less divergent pressure profile than a small fragment. This type of model is consistent with the experimental observation made by Held [3]. He observed that when shaped charge jets impact HE, the detonation threshold is based on a simple criteria that says that $V^2 D = \text{constant}$ [3], where V is the velocity of the fragment, and the D is the effective diameter. This observed fit implies a linear jet diameter dependence and quadratic velocity dependence. This means that the dispersive effects seem to take on the characteristic projectile dimension. Since the jet has a significant length, the time scale of the pulse is considered to be long compared to the void collapse time. This is one of the reasons why the expression does not take into consideration the pulse width. The set of experiments that do take into consideration the pulse width are covered by the $P^2\ \tau$ criterion [4]. This criterion states that for a planar shock, the initiation of HE is governed by $P^2 \tau = \text{constant}$ where τ is the duration of pressure pulse of magnitude P. If the combination of pressure and time exceeds a certain criteria (HE dependant property) then detonation will be observed. These two effects tend to explain / predict the behavior of a majority of HE detonation initiation conditions.

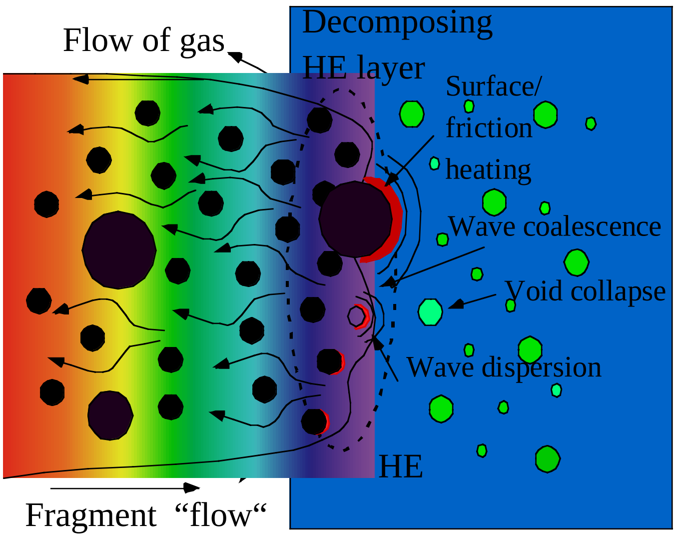

FIGURE 1- Illustration of various mechanisms by which HE initiation can take place.

One set of unanswered questions tends to revolve around attempting to predict how HE responds to impacts of many fragments whose size and velocity are below the individual fragment size threshold conditions. What is the effective proximity needed for multiple fragments to start acting coherently? What is the coherence mechanism? Local energy deposition (surface heating due to friction)? Void collapse? Wave coalescence? Fig 1 illustrates several effects that can play a role in changing the detonation threshold. In the planar impact example, the dominant energy transfer mode is by shock transfer from the projectile to the HE. The friction between the flier plate and the HE is minimal. It would be reasonable to assume that the initiation is a function of void compression, causing rapid heating, and growth to a detonation. For the case where a projectile/fragment impacts the HE the energy can be transferred to the HE by two mechanisms. The first mechanism is the same as for the planar system i.e. the shock. The second mechanism is energy dissipated by friction and shear from the projectile into the HE. This penetration work / dissipation can then be thought of as thermal energy source or a hot spot. The main question is how the energy is partitioned and how the fragment size affects this partitioning.

If surface area is important, the rate of energy transfer per fragment will increase with the fragment size. If the surface area per unit incoming kinetic energy is important, then the answer changes. Since the kinetic energy depends on mass and velocity, and the surface area depends on the fragment size and the number of fragments, then the frictional surface area scales inversely with fragment diameter. This means that that “surface heating” by a shower of many small fragments is larger then the heating produced by a few large fragments with equivalent kinetic energy.

From the HE safety perspective one could incorrectly conclude that initiating a detonation is most likely caused by the largest fragment. These effects are addressed by the models developed in the next section.

QUALITATIVE MODELS

The objective of setting up a qualitative model is to examine trends associated with some scaling parameters of interest. Two qualitative models can be hypothesized to affect the detonation threshold. Both of these models originate from a concept that to initiate a detonation, a region of HE has to be elevated in its energy state and given time to react. The increase in energy state can be achieved by depositing the energy, generating the energy or preventing the energy from leaving the region. All these phenomena are rate dependant and sensitivity to various parameters need to be addressed.

Qualitative Model #1 - Enhanced Energy Deposition

To determine the effect of fragment size on the energy transfer rate to the HE, energy flux is defined as the product of kinetic energy per fragment, the fragment number density multiplied by the velocity. This can further be expressed in terms of fragment density and average volume fraction. The energy flux given by Equation 1 is

$$\phi = \frac{1}{2} m v_p{}^2 N v_p = f \frac{1}{2} \rho_p v_p{}^3, \qquad (1)$$

where m is the mass of the fragment, v_p is the velocity of fragment, and N is number of fragments per unit volume, ρ_p is the density of the fragments. The symbol f represents the volume fraction occupied by fragments and is given by Equation 2

$$f = \frac{V_p}{V_t} = \frac{\frac{4}{3}(\pi r^3)}{\pi r^2 L} = \frac{4r}{3 v_p \tau}. \qquad (2)$$

where V_p and V_t are volumes occupied by fragments and total volume respectively, r is the fragment radius, τ_p is the time between fragments (or inverse frequency of fragments crossing a plane perpendicular to the flow). This model assumes that the frequency is only dependent on the position. To evaluate the effective energy deposition rate into the HE, Equation 2, is substituted into Equation 1 and differentiated with respect to position. The remaining unknown is the fragment deceleration rate which can be determined by using the conservation of momentum, and is given by Equation 3

$$F = m_p \frac{dv_p}{dt} = C_d \frac{1}{2} \rho_{HE} v_p^2 \qquad (3)$$

where C_d is the coefficient of drag, and ρ_{HE} is the density of HE. Defining ψ as the ratio of the HE density to the fragment density, and rearranging Equation 3, the volumetric energy deposition rate, ϕ_x, due to the fragments slowing down in HE is given by Equation 4.

$$\phi_x = \frac{3 C_d \phi \psi}{\pi r^3} \qquad (4)$$

There are two interesting conclusions drawn from this prediction. For a shower of fragments with a constant energy flux, increasing the average fragment size decreases the volumetric energy deposition rate. This relationship follows an inverse cube dependence with the fragment radius. As an individual fragment becomes larger, it carries more momentum and the surface area to volume ratio becomes smaller. This means that the fragment stopping distance increases with size and therefore energy deposited per unit depth and unit mass decreases with fragment size. The second effect has to do with the density ratio of the fragment relative to the medium it is impacting. The model indicates that as the density of the target increases relative to the density of the fragment, the scaled volumetric energy deposition rate increases.

Qualitative Model 2: Preventing The Loss of Energy by Choking the Out-Flow

When fragments deposit their energy in the HE, this energy can cause local reactions to take place and the HE can decompose. The gasses that result in this decomposition remove energy from the reaction zone as they leave. If the gasses are prevented from leaving, the local energy can build up. When a field of fragments is flying in a close proximity to each other, the cloud has a certain porosity and permeability. The porosity is typically defined as the volume fraction that the pores occupy in a two-phase mixture. The permeability for a fluid flowing though a packed bed can be given by Equation 5.

$$k = cr^{2.2}\eta^{5.1} \tag{5}$$

Where k is the permeability, η is the porosity and r is the scaled fragment radius and c is a constant. This is an empirical expression traditionally used in petrophysics [7], in predicting flow of petroleum through underground reservoirs. Using the Darcy law, the pressure gradient caused by the volumetric flux, u, and the dynamic viscosity μ is given by Equation 6.

$$\frac{dP}{dx} = \frac{u\mu}{cr^{2.2}\eta^{5.1}} \tag{6}$$

This simplistic model shows that for a given flow rate changing the fragment size by three orders of magnitude, results in a pressure gradient that changes by more than six orders of magnitude. This mechanism can certainly change the energy release rate from the interaction zone.

Both Model 1 and Model 2 point to the same conclusion. As the fragment size decreases, given the same incoming kinetic energy, volumetric energy deposition rate increases, and the energy loss rate is reduced, providing an increased tendency to initiate a detonation. This hypothesis is further computationally analyzed in the next section.

QUANTITATIVE MODEL

The previously discussed models were examined simply to determine trends. This section attempts to adapt existing computational methods and models to predict detonation thresholds and compare the results with the trends predicted in previous section. An existing computer hydro code that uses an arbitrary-lagrangian-eularian method was adapted for examining thresholds. One of the modeling methods that is available for predicting initiation of a detonation of the HE is the Cochran-Tarver [8] reactive flow model that simulates in a detailed way how heterogeneous explosives initiate and burn. This model has been validated to predict the ignition of HE caused by fragments that are greater then 1 cm in diameter. It is not clear if this model can be extended to smaller sizes and multiple fragments. However, as an academic exercise the model is applied to multiple fragments whose size is smaller than the validated size to study the coalescence of shocks that form from multiple fragments and attempt to determine its ultimate effect on the HE. In addition to examining the effects of coalescence of shocks, the exercise also examines the regional energy deposition rate that is related to the fragment size.

The process of computationally depositing energy into HE from many fragments is not trivial. Tracking many fragments is computationally difficult. Therefore, energy deposition is performed using a tracer particle model. The tracer particle is capable of exchanging energy and momentum with the surroundings through the coefficient of drag. As an approximation, the value for the coefficient of drag was chosen to be equal to one. A measured coefficient of drag for Re number ~ 10^6 and Mach number 5, is ~ 0.9 [6]. The calculations to determine the detonation thresholds were conducted by defining a fixed HE geometry and launching fragments of uniform size. The location of the fragments within the fixed geometry was chosen using a random number generator. Initially the examined cloud volume was a disc whose diameter was 1 cm and whose thickness was 0.5 cm. The speed of all fragments was 4 km/sec. The only parameter that was varied in the problem was the number of fragments. The calculation was conducted repeatedly each time increasing the number of fragments for a fixed fragment size until the detonation was calculated. For each calculation, an effective cloud density was determined. This identical calculational sequence was completed for a range of fragment sizes. Next, a smaller series of calculations were done for a smaller and a larger cloud diameter. For a large fragment size, the detonation thresholds converged to a similar value since only one fragment was needed to set off a detonation. The results are displayed in Fig 2.

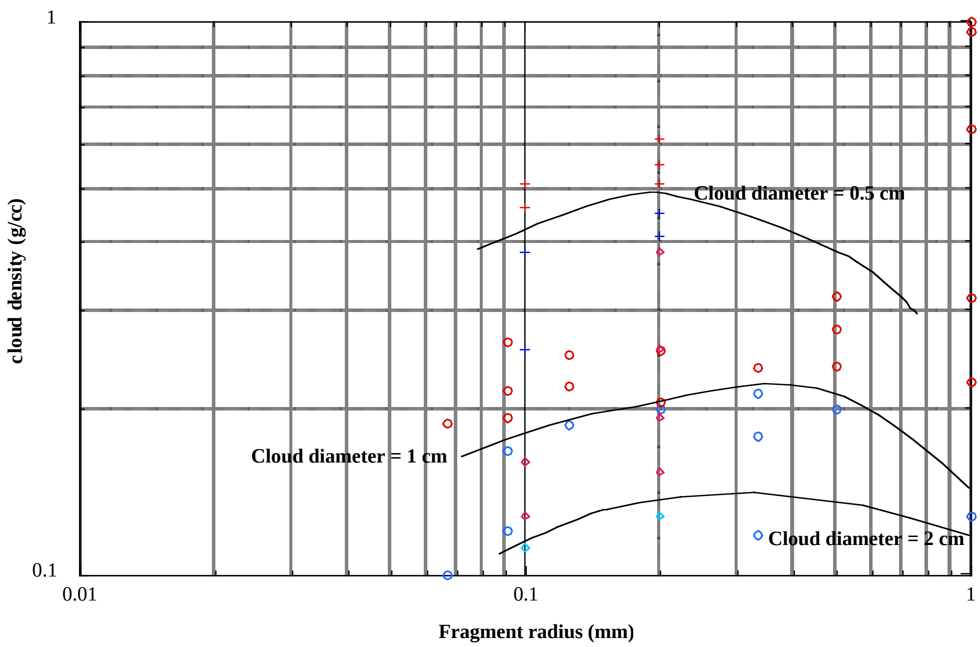

FIGURE 2 - Plot showing the computed detonation threshold for various fragment sizes and effective cloud densities required to initiate a detonation. This calculation was done for three effective cloud diameters.

The results show that a cloud density needed to initiate an HE detonation peaks as a function of fragment size. This makes sense if two separate HE initiation mechanisms are in place that can cause detonations. One mechanism is the shock compression mechanism and the second mechanism is a rapid increase in energy density. When a fragment is large, a shock spawned from the fragment is sufficient to cause a detonation. If the fragments are small, then the enhanced energy transfer rate in conjunction with the choking effect is the mechanism. Also, if the cloud diameter is increased the incident energy required to initiated a detonation decreases. The opposite trend is followed for reducing the cloud diameter. The models presented in previous section seem to show a much larger sensitivity to the fragment size than the computational model in this section. The simple models predict that the effect of reducing the fragment size by one order of magnitude introduces changes of three orders of magnitude whereas the computational model for the same fragment size only predicts a 30 % change. Some of the differences can be explained by the multidimensionality of the problem.

SUMMARY

This paper has qualitatively and quantitatively addressed the issue associated with how multiple fragments can initiate a detonation. Simple relationships derived using energy deposition rates and choking limits, show that for a large number of fragments reducing the fragment size increases the energy density deposited in the HE. The computational model using reactive flow indicates that the magnitude of this effect is not as large as the analytic equations suggest. The second effect not predicted analytically but predicted by reactive flow is that for a few fragments the detonation has a lower threshold then with a larger number of fragments. The result indicates that a non-linear size-density dependence seems to exist that will initiate a detonation. Insufficient experimental data exists at this time to confirm this finding.

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